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(54) **Title:** HAIR FOLLICLE GRAFT FROM TISSUE ENGINEERED SKIN

(57) **Abstract:** The present invention provides a hair graft comprising (a) tissue engineered skin comprising a tissue engineered epidermal layer, a tissue engineered dermal layer, and hair follicle progenitor cells and (b) a scaffold. The invention also provides methods of making and using the hair grafts of the present invention.

# HAIR FOLLICLE GRAFT FROM TISSUE ENGINEERED SKIN

## CROSS REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of U.S. Provisional Application No. 60/738,931, filed November 22, 2005, which is incorporated by reference herein.

## BACKGROUND

**[0002]** Hair loss may occur due to a variety of conditions and may affect anyone: men, women and children. Hair loss conditions include, but are not limited to, alopecia capitis totalis, i.e., loss of all scalp hair, alopecia universalis, i.e., loss of hair over the whole body, alopecia areata, i.e., patchy hair loss, and androgenetic alopecia, i.e., male pattern baldness. Medications are available to treat alopecia including minoxidil, finasteride, corticosteroids and anthralin. However, any new hair growth resulting from the medication generally stops upon discontinuation of the medication.

**[0003]** More aggressive hair restoration methods include hair transplants and scalp reduction surgery. Hair transplantation entails excision of a full-thickness strip of scalp tissue from the back of the head, dissecting the excised scalp tissue into hundreds of "follicular unit grafts", each containing from one to several hairs, and implanting the grafts into recipient sites created by making stab wounds in the bald sections of the scalp. Hair transplantation creates no new hair follicles and often not all of the explanted follicles successfully transplant. Scalp reduction surgery, which is becoming less popular, aims to surgically reduce the area of bald skin on subject's head. Both hair transplantation and scalp reduction surgery are expensive and may be painful. Moreover, both carry possible risks of infection and scarring.

**[0004]** It is well known that specific cells within the hair follicle, including epidermal stem cells and dermal papilla cells, have the capacity to induce follicle neogenesis. Attempts have been made to exploit the inductive capabilities of these cells, including injecting dermal papilla cells directly into the skin and implanting plucked hairs carrying

epithelial cells having various proliferative and differentiative characteristics. Previous attempts at producing follicle neogenesis have failed to produce reliable, reproducible and cosmetically satisfactory results.

## SUMMARY

[0005] In one embodiment, the present invention provides a hair graft comprising (a) tissue engineered skin comprising a tissue engineered epidermal layer, a tissue engineered dermal layer, and hair follicle progenitor cells and (b) a scaffold, wherein the scaffold is at least 2 millimeters thick.

[0006] In other embodiments, the invention provides methods of making and using the hair grafts of the present invention.

## DETAILED DESCRIPTION

[0007] The present invention provides a novel graft for hair follicle formation comprising a layer of tissue engineered skin comprising a tissue engineered epidermal layer and a tissue engineered dermal layer and hair follicle progenitor cells on a bioabsorbable scaffold. Tissue engineered skin by itself is suitable for transplantation. However, it is extremely thin and difficult to manipulate using traditional hair graft techniques. The scaffold provides rigidity and stability to the tissue engineered skin so that the graft can be easily manipulated.

[0008] The tissue engineered skin may be prepared by any suitable method known to one skilled in the art. For example, human neonatal foreskin tissue can be used as a source of human dermal fibroblasts that are multiplied in culture and seeded onto a scaffold such as collagen gel to provide a tissue engineered dermal layer. Epidermal keratinocytes can be obtained from the same neonatal tissue or, alternatively, obtained from plucked hair follicles. A tissue engineered epidermal layer can be produced from plucked hair follicles as disclosed in U.S. Patents 6,730,513, 6,673,603, 6,548,058, 5,968,546, and references cited therein, the teachings of which are incorporated by reference herein. The tissue engineered dermal layer and tissue engineered epidermal layer can be separately prepared and then assembled into tissue engineered skin with hair

follicle progenitor cells dispersed therein, suitably sandwiched between the two assembled layers. The tissue engineered dermal and epidermal layers can be prepared without the use of a scaffold, for example by the method described by Pouliot, *et al.* in *Transplantation*, 2002 Jun 15;73(11):1751-7, and references cited therein, the teachings of which are incorporated by reference herein.

**[0009]** In one embodiment, the tissue engineered skin containing follicle progenitor cells is placed on a bioabsorbable scaffold of suitable thickness to form a construct and is cultured further *in vitro* until the living skin construct is firmly attached to the bioabsorbable scaffold. In another embodiment, the tissue engineered dermal layer is placed on a bioabsorbable scaffold. Hair follicle progenitor cells are placed on the dermal layer and then a tissue engineered epidermal layer is placed on top of the hair follicle progenitor cells to form a construct. Alternatively, the tissue engineered dermal layer can be formed on a bioabsorbable scaffold. Hair follicle progenitor cells are then placed on the dermal layer and a tissue engineered epidermal layer is placed on top of the hair follicle progenitor cells.

**[0010]** In another embodiment, the tissue engineered dermal layer can be prepared on a bilayer scaffold comprising a bottom layer of an artificial skin implant, such as the Integra Dermal Regeneration Template™ (Integra NeuroSciences, Plainsboro, New Jersey) in which the silicon rubber layer has been removed and replaced with a top layer of collagen. The collagen coating is then seeded with dermal fibroblasts and cultured *in vitro*.

**[0011]** Suitably, the hair follicle progenitor cells may be mesenchymal stem cells, dermal papilla cells, dermal sheath cells, follicular epidermal stem cells, also known as "bulge" cells, or any combinations thereof. Suitably, the progenitor cells are aggregated or clumped together prior to placement in the tissue engineered skin. The size of the aggregates is suitably from about 10 to about 500 microns, or about 20 to about 200 microns or about 30 to about 60 microns.

**[0012]** The construct comprising the tissue engineered skin containing hair follicle progenitor cells and the bioabsorbable scaffold is then cut into grafts suitable for

implantation into the skin. The construct is cut such that grafts with the epidermal layer facing one direction and the scaffold facing the opposite direction are formed. The size and shape of the cuts is optimized such that little or no construct is wasted and the longest dimension is perpendicular to the tissue layers. The grafts are suitably cut into a size that is equivalent to a single hair graft, a follicular unit graft or modified follicular unit graft. Typically, these grafts are about 1 to about 9 square millimeters in surface area, or about 2 to about 8 square millimeters, or about 4 to about 6 square millimeters. The thickness is suitably about the same as the thickness of scalp skin. Suitably, the graft is at least about 2 millimeters thick, or at least about 5 millimeters thick, or at least about 8 millimeters thick, or at least about 10 millimeters thick. As used herein, "thick" is used to describe the height of the graft, i.e. the z-axis of the graft.

**[0013]** The bioabsorbable scaffold is a non-cytotoxic structure or substance that is capable of containing or supporting living cells and holding them in a desired configuration for a period of time. The term "bioabsorbable" refers to any material the human body can break down into non-toxic by-products that are excreted from the body or metabolized therein. Suitable bioabsorbable materials for the scaffold include, but are not limited to, poly(lactic acid), poly(glycolic acid), poly(trimethylene carbonate), poly(dimethyltrimethylene carbonate), poly(amino acids)s, tyrosine-derived poly(carbonates)s, poly(carbonates)s, poly(caprolactone), poly(para-dioxanone), poly(esters)s, poly(ester-amides)s, poly(anhydrides)s, poly(ortho esters)s, collagen, gelatin, serum albumin, proteins, polysaccharides, mucopolysaccharides, carbohydrates, glycosaminoglycans, poly(ethylene glycols)s, poly(propylene glycols)s, poly(acrylate esters)s, poly(methacrylate esters)s, poly(vinyl alcohol), hyaluronic acid, chondroitin sulfate, heparin, dermatan sulfate, versican, copolymers, blends and mixtures of polymers, and oligomers containing bioabsorbable linkages.

**[0014]** For example, hyaluronic acid may be converted into an insoluble crosslinked material ("HAX") by treatment with a condensing agent, suitably 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide ("EDC"). Alternatively, hyaluronic acid may be converted into an insoluble material by esterification, e.g., the benzyl ester of hyaluronic acid, and used to prepare the bioabsorbable scaffold. Suitably, trans-esterification

crosslinked HAX is used because the resultant product is then converted back into soluble hyaluronic acid upon hydrolysis of the ester linkages. Hydrolysis of the ester linkages takes place within a few days *in vivo*. Various cross linking agents may be employed including, but not limited to, aliphatic diamines, diaminoacid esters such as alkyl esters of lysine, and amine-terminated poly(ethylene glycol).

**[0015]** Various molecular moieties may be associated with the bioabsorbable scaffold using, for example, surface modifications, graft polymerization, copolymerization of bioabsorbable materials or blending of at least one moiety and the bioabsorbable material(s) used in forming the bioabsorbable scaffold. Moieties that may be associated with the bioabsorbable scaffold include, but are not limited to, growth factors, cell attachment binding site moieties, angiogenesis factors, cell signaling molecules, other small molecules, e.g., drugs that enhance hair follicle regrowth such as monoxidil, glycoproteins, e.g., chondroitin sulfate, dermatan sulfate, and versican, other bioactive molecules or combinations thereof.

**[0016]** Association of at least one moiety with the bioabsorbable scaffold may suitably be advantageous for improved association between various types of hair follicle progenitor cells and/or improved cell function, cell aggregation or cell initiation of the follicle neogenesis process. Attached moieties, such as growth factors and angiogenesis factors, may be released during the degradation of the bioabsorbable scaffold and encourage blood vessel growth into the newly formed follicle. Attachment of higher molecular weight moieties, such as proteins, glycoproteins, and other biopolymers, such as collagen, laminin, and fibronectin, may be physically or electro-statically bound to the bioabsorbable scaffold to suitably provide greater physical integrity, cell attachment capacity, or bioactivity.

**[0017]** For example, association of bioactive molecules to the HAX structure suitably enhances the performance of the resultant scaffold, e.g., association of peptides containing the cell attachment domain sequence of amino acids Arg-Gly-Asp (RGD) may be used to enhance dermal papilla cell attachment to the scaffold.

[0018] The term "growth factor" refers to a naturally occurring protein capable of stimulating cellular proliferation and cellular differentiation. Growth factors are important for regulating a variety of cellular processes. Well-known growth factors suitable for use in the present invention include, but are not limited to, granulocyte-colony stimulating factor ("G-CSF"), granulocyte-macrophage colony stimulating factor ("GM-CSF"), nerve growth factor ("NGF"), neutrophins, platelet-derived growth factor ("PDGF"), erythropoietin ("EPO"), thrombopoietin ("TPO"), myostatin ("GDF-8"), growth differentiation factor-9 ("GDF9"), basic fibroblast growth factor ("bFGF" or "FGF2"), epidermal growth factor ("EGF"), placenta derived growth factor ("PLGDF"), and hepatocyte growth factor ("HGF").

[0019] Similarly, the term "angiogenesis factor" refers to a naturally occurring protein capable of stimulating angiogenesis. Suitable angiogenesis factors for the present invention include, but are not limited to, vascular endothelial growth factor ("VEGF"), endothelial cell stimulating angiogenesis factor ("ESAF") and any nonmitogenic angiogenesis factors present in wound fluid.

[0020] The term "cell attachment binding site moiety" refers to a protein that plays a role in cell-cell/cell-matrix interaction and cellular communications. Examples of suitable cell attachment binding site moieties include, but are not limited to, integrins, cadherins, cell adhesion molecules ("CAMs"), selectins, fibronectin and fibronectin fragments including synthetic fribonectin-mimetic binding sites such as the RGD amino acid sequence.

[0021] The term "cell signaling molecule" refers to a chemical involved in transmitting information between cells. Such molecules are released from the cell sending the signal by crossing over the gap between cells, interacting with receptors in another cell, and triggering a response in that cell. Cell signaling molecules naturally are part of a complex system of communication that governs basic cellular activities and coordinates cell actions. These include nitric oxide and various steroids.

[0022] The term "bioactive molecule" refers to any molecule that has pharmacological activity that is beneficial to hair follicle neogenesis and survival.

Suitable bioactive molecules may include, but are not limited to, cell signaling agonists or antagonists.

[0023] In another embodiment of the present invention, the grafts are manually implanted in wounds created in the desired implantation site using techniques similar to those used with traditional follicular units. Alternatively, the hair graft and bioabsorbable scaffold combination may be implanted using the "stick and place" method of grafting. In the "stick and place" method, the skin is pierced with the sharp point of a hollow needle or tube that also serves as a container for the bioabsorbable scaffold ensheathed hair graft. The tube is then inserted into the wound and withdrawn against a push rod that prevents the graft from coming out of the tube and ensures correct placement of the graft. A modification of the "stick and place" method may use a tool such as the Choi implanter, which requires breaking the skin with a pointed instrument prior to inserting the tube and depositing the implant.

[0024] In a further embodiment of the present invention, the scaffold used to provide sufficient thickness to the tissue engineered follicle progenitor cell-seeded skin is the same scaffold as that used to create the tissue engineered dermal layer. Thus, the scaffold for this purpose may have an isotropic structure such that the surface is designed for accepting dermal fibroblasts and facilitating their multiplication and maturation into a tissue engineered dermal layer, whereas the bulk of the scaffold is a porous structure designed to allow rapid tissue ingrowth upon implantation. A suitable scaffold for this purpose can be prepared, for example, by coating the surface of a highly porous synthetic or cross-linked biopolymer scaffold to be seeded with dermal cells with a layer of collagen or other suitable biopolymer or cell-compatible substance. After the dermal skin cells are confluent with the surface of the scaffold the hair follicle progenitor cells or aggregates thereof are placed on top of the dermal tissue equivalent and allowed to attach. A tissue engineered epidermal layer is placed on top of the hair follicle progenitor cells to complete formation of the construct. The construct is cultured further while submerged in culture medium and then brought to the air interface to allow the epidermis to mature to complete the formation of tissue engineered skin, as is standard practice in the art of producing tissue engineered skin.

[0025] In a further embodiment of the present invention, the scaffold that provides thickness to the tissue engineered follicle progenitor cell-seeded skin can also serve as a vehicle to add other cells to the graft that provide a beneficial effect. These cells may include, for example, fat cells, pre-adipocytes, endothelial cells, and bone marrow cells. These additional cells suitably are autologous cells obtained from the patient in need of the hair graft. Thus, the tissue engineered skin components of the graft can be obtained from neonatoal foreskin, the follicle progenitor cells can be obtained from a scalp biopsy of the patient in need of hair restoration, and the supplemental cells optionally also can be obtained from the patient. The use of these added cells, which produce important beneficial growth factors, obviates the need for or complements the effectiveness of the above mentioned growth factors. The endothelial cells, fat cells, and pre-adipocytes can be obtained from liposuction fat removed, for example, from the patient's abdominal fat and the bone marrow cells can be obtained, for example, by aspiration from the patient's hip bone.

[0026] The wounds in the desired implantation site may be made by any suitable technique. For example, the wounds may be made using a sharp instrument, such as a scalpel, trochar or needle, or the wounds may be made by a laser or by a punch. Suitably, the needle is an 18 or 19 gauge needle. The depth of the wound can be pre-determined by properly adjusting the protrusion length of a spear-point blade attached to a handle equipped with a threaded fastener made for this purpose. For example, SP90 and SP91 blades (Swann-Morton Surgical, Sheffield, UK) with four sided spear-point tips were specially designed to allow control over depth and angle while creating recipient sites for hair follicle graft implantation.

[0027] A protectant may be placed in the wound prior to, during or following implantation of the hair graft. The term "protectant" refers to any substance of temporary duration that serves to protect the cells from trauma associated with implantation or destruction by the inflammatory process of wound healing. Many commercially and clinically available substances may be used as a protectant. Suitable protectants include, but are not limited to, collagen, hyaluronic acid, and chondroitin sulfate solutions. One suitable protectant is autologous serum from the subject in which the hair graft is

implanted. Autologous serum may be obtained by drawing a small amount of whole blood from the subject and removing the cells by centrifugation. Advantages of using autologous serum include providing an anchor for the hair graft via natural clotting properties associated with the serum. Also, the autologous serum may contain nutrient molecules and other native beneficial factors to further nurture follicle neogenesis.

**[0028]** The grafts and methods of the present invention can be used to create new hair follicles and new hair on any region of the subject where new hair is desired. Suitably, the grafts and methods of the present invention are utilized to develop new hair on the scalp or eyebrow region of the subject. The subject may be any mammal. Suitably, the subject is a human.

**[0029]** It is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

**[0030]** As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise. It should also be noted that the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise. All publications, patents and patent applications referenced in this specification are indicative of the level of ordinary skill in the art to which this invention pertains. All publications, patents and patent applications are herein expressly incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually indicated by reference. In case of conflict between the present disclosure and the incorporated patents, publications and references, the present disclosure should control.

[0031] It also is specifically understood that any numerical range recited herein includes all values from the lower value to the upper value, i.e., all possible combinations of numerical values between the lowest value and the highest value enumerated are to be considered to be expressly stated in this application. For example, if a concentration range is stated as 1% to 50%, it is intended that values such as 2% to 40%, 10% to 30%, or 1% to 3%, etc., are expressly enumerated in this specification.

[0032] The following examples are provided to assist in a further understanding of the invention. The particular materials, methods and conditions employed are intended to be illustrative of the invention and are not limiting upon the scope of the invention.

**Examples**

**Example 1:**

[0033] Human dermal fibroblasts are obtained from newborn infant foreskin tissue and cultured. The cultured cells are seed on a bioabsorbable scaffold with a silicon rubber film backing. A piece of dorsal skin is excised from a nu/nu mouse without disturbing the underlying blood vessels. The seeded scaffold is implanted on the wound and the *in situ* blood supply maintains the viability of the seeded scaffold. After an appropriate healing time elapses, the silicone rubber backing is removed and hair follicle progenitor cells are delivered to the vascularized dermal tissue equivalent. The hair follicle progenitor cells are covered with an epidermal layer. The wound is allowed to heal and new hair follicles are formed.

**Example 2:**

[0034] Human dermal fibroblasts and keratinocytes are obtained from newborn infant foreskin tissue and cultured according the procedures developed by Professors Auger and Germain (see, Pouliot, *et al.* in *Transplantation*, 2002 Jun 15;73(11):1751-7, and referenced cited therein) to produce separate tissue engineered dermal and epidermal layers. A porous dermal regeneration template (5 mm thick) comprised of collagen and glycosaminoglycan, such as that sold by Integra Life Sciences, Inc. (Plainsboro, New Jersey), is aseptically rinsed with sterile DMEM/F12 culture medium, and combined with

the tissue engineered dermal layer and incubated in a cell culture incubator until the tissue engineered dermal layer and dermal regeneration template are attached. Dermal papilla cells are placed on top of the dermal layer and allowed to attach. The tissue engineered epidermal layer comprised of a sheet of keratinocytes is carefully transferred onto the papilla cell-seeded dermal tissue to complete the assembly of tissue engineered dermal layer and epidermal layer with dermal papilla cells sandwiched in between. This construct is cultured further until it possesses sufficient integrity, and then it is cultured with the epidermal layer exposed to air to induce the formation of mature skin according to standard procedure. The construct is than transported into the operating room where the patient is anesthetized and the surgeon creates recipient sites for the grafts with a spear-point blade, as is traditionally done with current follicle transplantation. Meanwhile, the technicians working with appropriate magnification and surgical tools cut the tissue engineered construct into "slivers" that are approximately 1 to 2 mm wide and are made by slicing the epidermal surface down to the bottom of the scaffold. The slivers are then cut into 1 to 2 mm wide pieces to produce graft that are typically 1 x 1 x 5 mm. These grafts are then loaded into the Choi implanter comprising a tube and push rod assembly. The graft goes in "head first" such that the epidermal surface is in contact with the push rod and the bottom of the scaffold is at the open end of the tube. The technician then inserts the tube into the recipient site and removes the tube while pushing on the push rod to deposit the graft exactly as planned by the surgeon. A properly implanted graft will have its epidermal layer in contact with the surrounding epidermis and the bottom of the scaffold will be at the level of the subcutaneous fat. The follicle neogenesis process initiated *in vitro* will continue *in vivo* such that new hairs will become visible at the implant sites within 3 to 6 months.

**Example 3:**

[0035] A tissue engineered graft is prepared and implanted as described in Example 2 except that pre-adipocytes and vascular endothelial cells are added to the porous scaffold just prior to combination with the tissue engineered dermal layer. All other steps are as described above.

**Example 4:**

**[0036]** A tissue engineered graft is prepared and implanted as described in Example 2 except that the scaffold is first coated with a solution of human collagen dissolved in 0.005M acetic acid and then is soaked and rinsed with buffered culture medium to insolubilize the collagen. Human foreskin fibroblasts are then seeded directly on the collagen coated scaffold and cultured until a tissue engineered dermal layer forms. The subsequent steps of seeding with papilla cells and layering with an epidermal sheet of keratinocytes are performed as previously stated.

CLAIMS

What is claimed is:

1. A hair graft comprising (a) tissue engineered skin having a tissue engineered epidermal layer, a tissue engineered dermal layer, and hair follicle progenitor cells; and (b) a scaffold, wherein the graft is at least about 2 millimeters thick.

2. The graft of claim 1, wherein the hair follicle progenitor cells are located between the dermal and epidermal layers.

3. The graft of claim 1, wherein a surface of the epidermal layer of the graft is about 1 to about 9 square millimeters in area.

4. The graft of claim 1, wherein a moiety is associated with the scaffold.

5. The graft of claim 4, wherein the moiety is selected from the group consisting of a growth factor, an angiogenesis factor, a cell attachment binding site moiety, a cell signaling molecule, a polypeptide, a glycoprotein, and a bioactive molecule.

6. The graft of claim 1, wherein additional cells are associated with the scaffold.

7. The graft of claim 6, wherein the additional cells are selected from the group consisting of fat cells, pre-adipocytes, vascular endothelial cells, and bone marrow cells.

8. The graft of claim 1, wherein the hair follicle progenitor cells comprise dermal papilla cells.

9. The graft of claim 1, wherein the hair follicle progenitor cells are aggregrated.

10. A method of making a hair graft, comprising:
    a) placing a tissue engineered dermal layer on a bioabsorbable scaffold;
    b) placing hair follicle progenitor cells on the tissue engineered dermal layer;
    c) placing a tissue engineered epidermal layer on the hair follicle progenitor cells to form a construct;

d) allowing the construct to mature *in vitro*; and

e) cutting the construct into implantable grafts.

11. A method of implanting a hair graft comprising creating a wound in skin of a subject and implanting the graft of claim 1 into the wound.